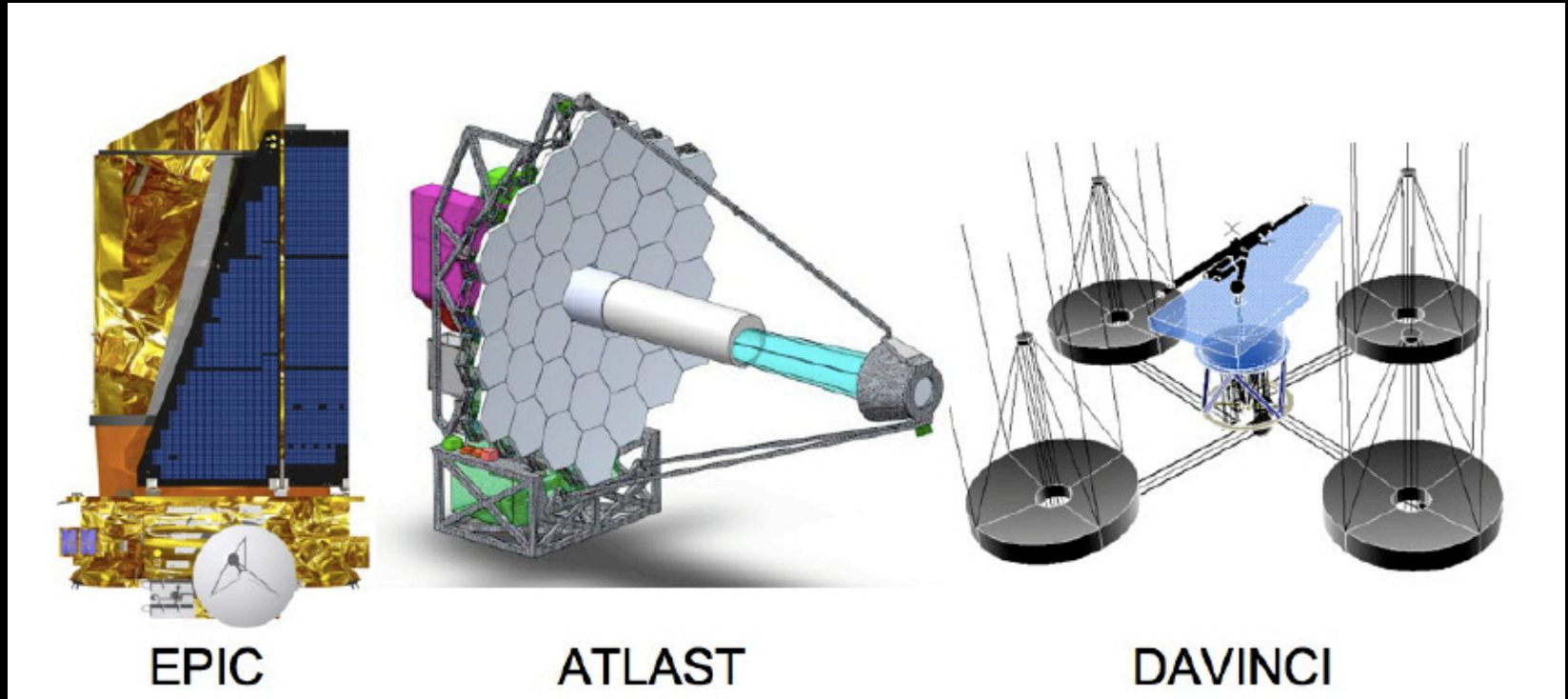


Visible Nuller Coronagraph Simulations

Bertrand Mennesson, JPL
(Presented by Jagmit Sandhu)

Visible Nuller Instrument is common to 3 separate NASA ASMC Coronagraph Studies:

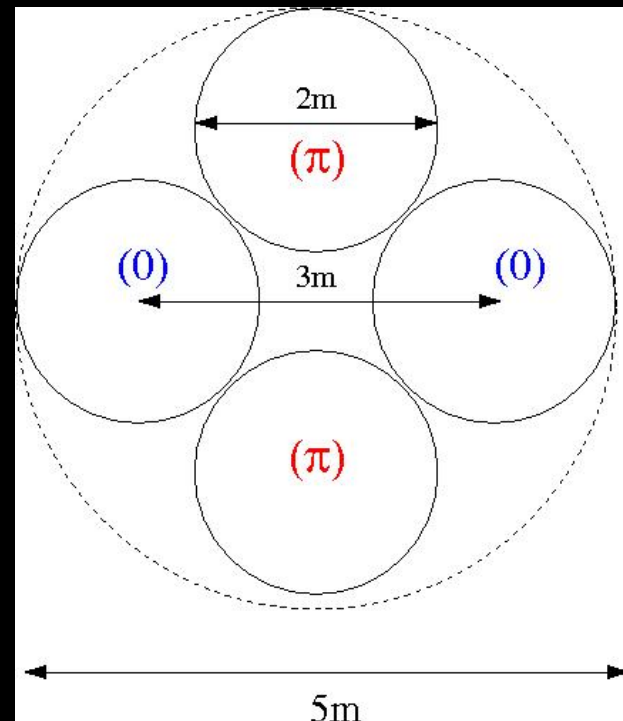


- ✓ EPIC : Extrasolar Planetary Imaging Coronagraph (Lyon, Clampin, Woodruff et al. 2010)
- ✓ ATLAST : Advanced Technology for Large aperture Space Telescope (Postman et al. 2010)
- ✓ DAVINCI : Diluted Aperture Visible Nulling Coronagraph Imager (Woodruff, Shao et al. 2010)

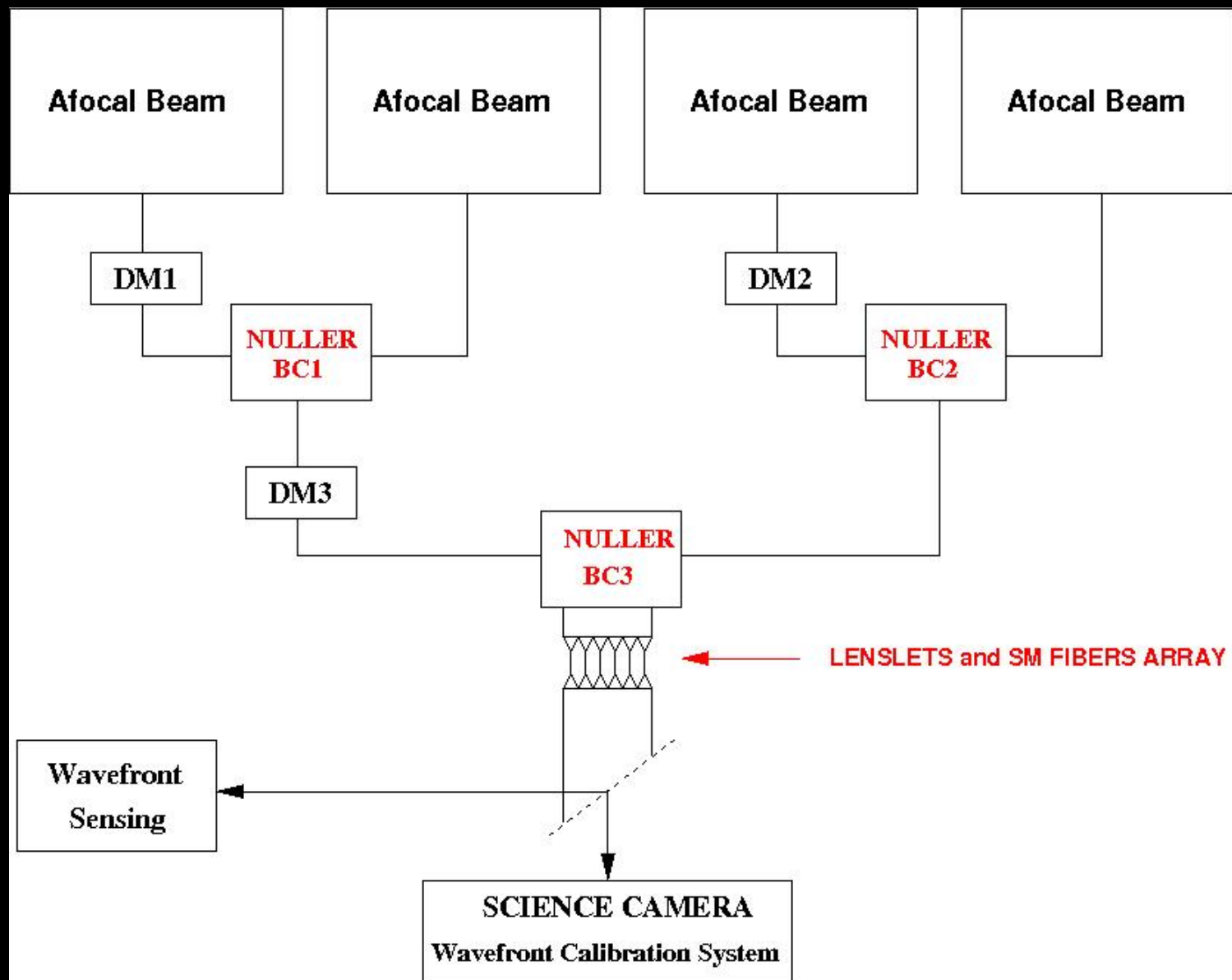
General Architecture Studied: 4 Beam Nulling

- ✓ Representative of all 3 ASMC studies (but assumes rigid body pointing)
- ✓ Can simulate arbitrary beam sizes and baseline lengths
- ✓ Simulates speckle fields in 4 x 20% BW filters centered at B, V, R, H
- ✓ Only V band results shown here

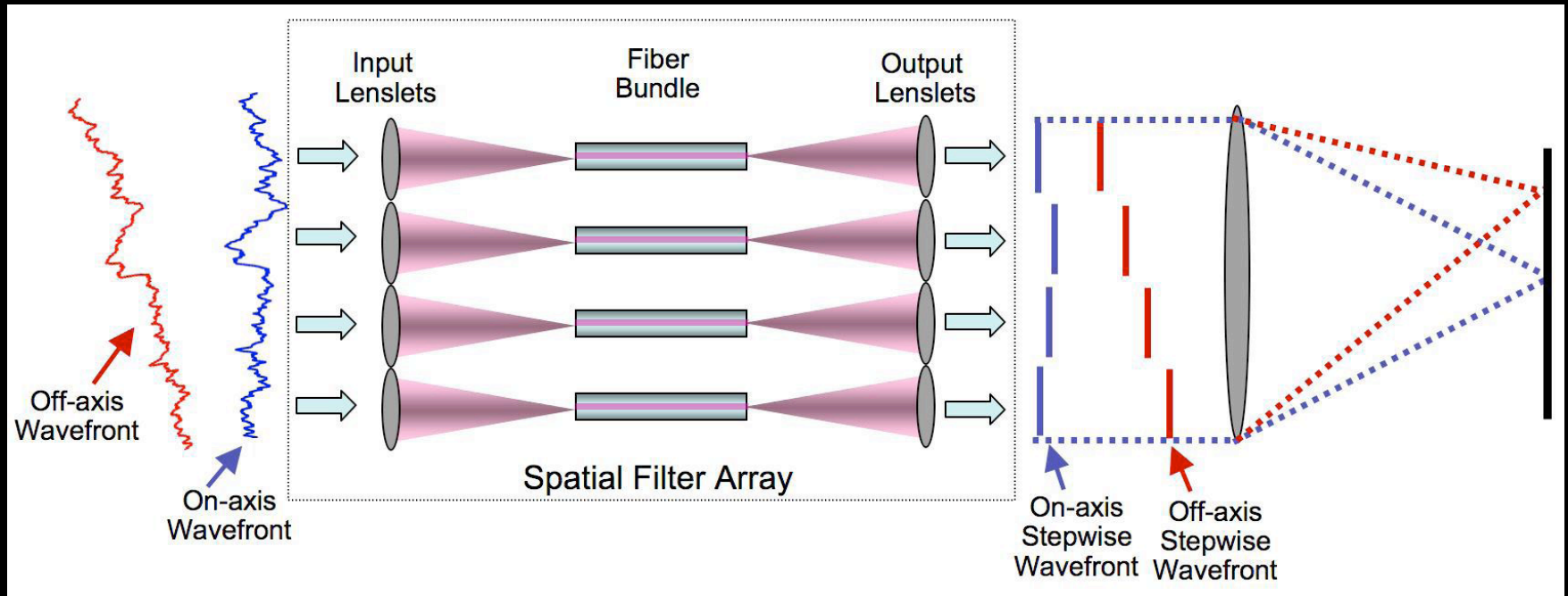
Used $D=2\text{m}$, $B=3\text{m}$ and V band for simulations presented here:



Instrument Block Diagram

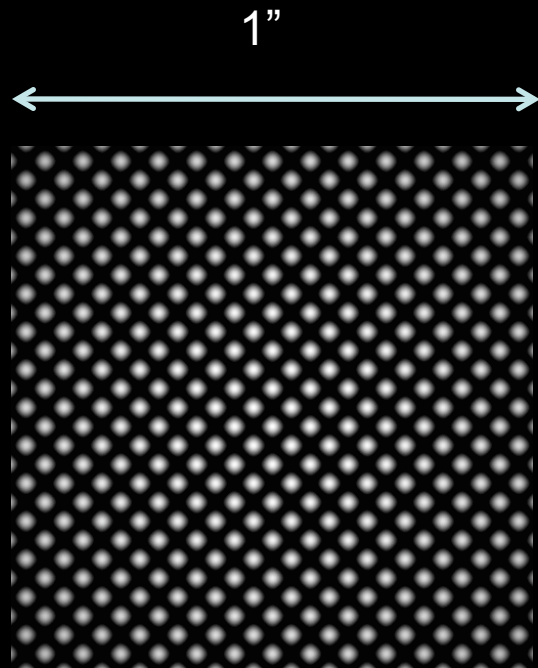


Zoom on SM Fiber Array

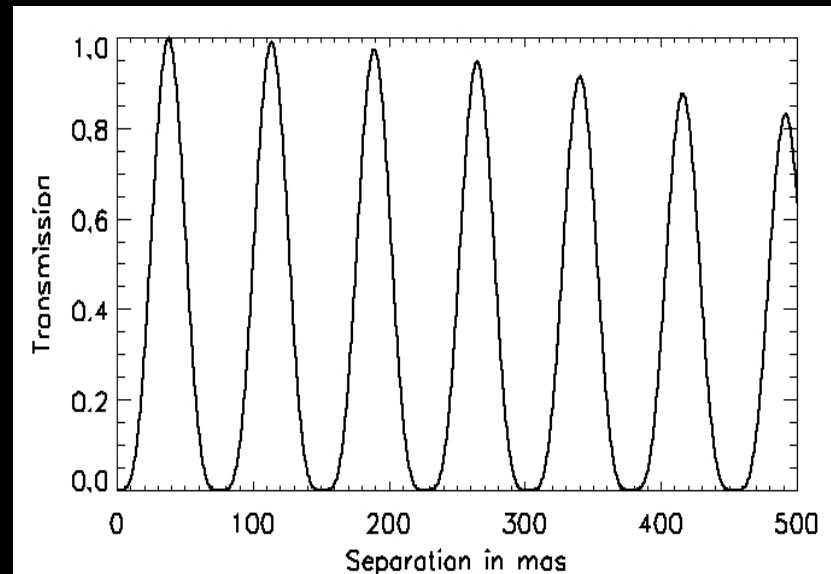


Simulations assume hexagonally shaped Array of 1027 SM Fibers
and hexagonally packed lenslets

Sky Transmission Pattern



Sky transmission pattern
(tapering due to SM fiber FOV)



Monochromatic transmission at 550nm along
X axis

Half power point is $(2/\pi) \lambda/B$
That is $0.85 \lambda/D$ with $D=4m$ (diameter
adopted for Lyot and external occulter
designs)

Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)

Simulations Principle and Building Blocks

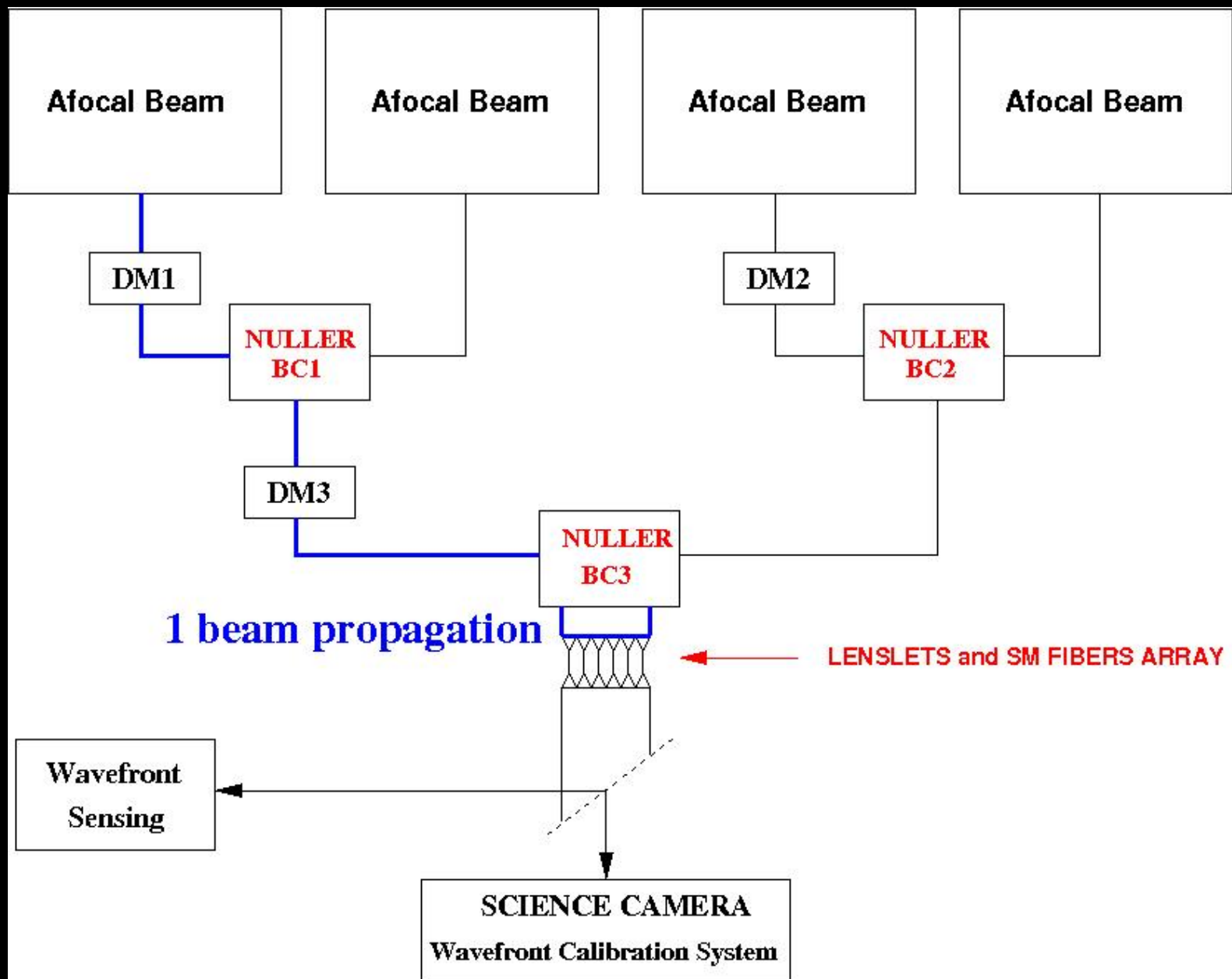
Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)
- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level

Simulations Principle and Building Blocks

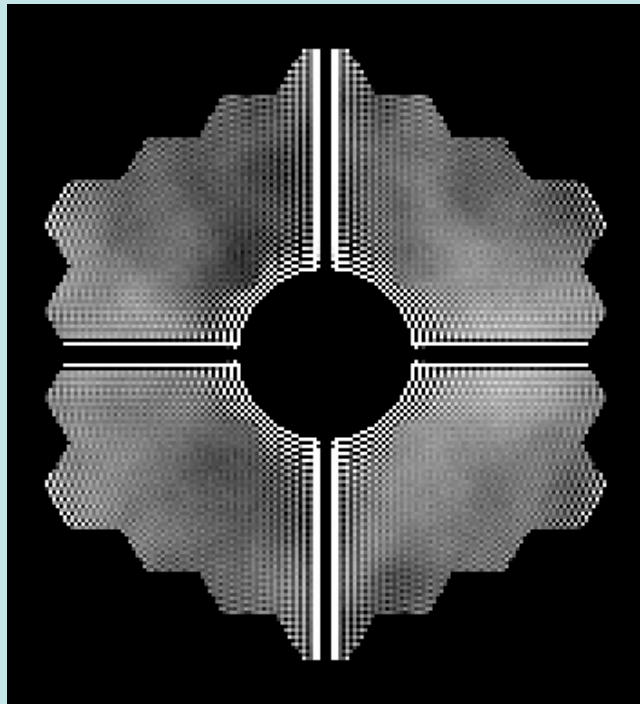
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- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level
 - ✓ Use “PROPER” Finite Diffraction Code to propagate individual beams (or telescopes) distortions to Fiber Lenslet Array



Individual Telescope (or Beam) Amplitude and Phase maps after propagation to 1st lenslets array

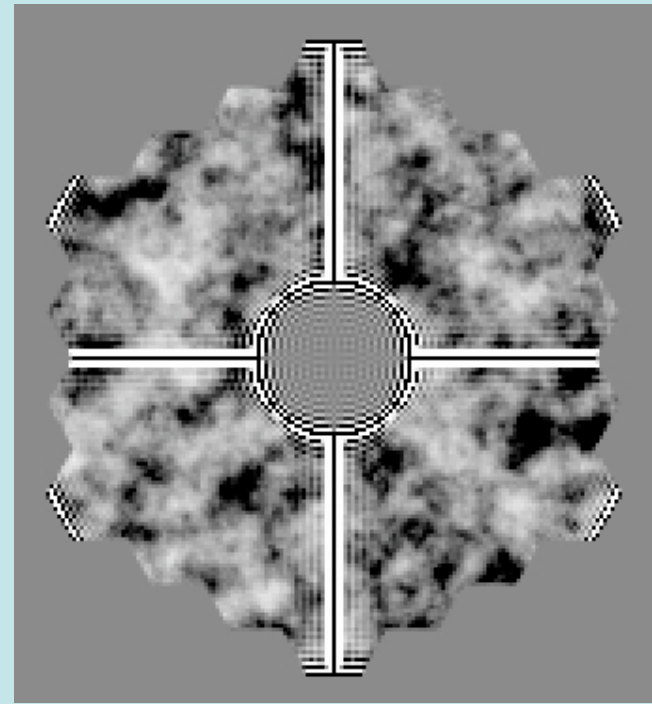
Amplitude Relative Fluctuations



-2×10^{-4}

2×10^{-4}

Phase (radians)



-2×10^{-4}

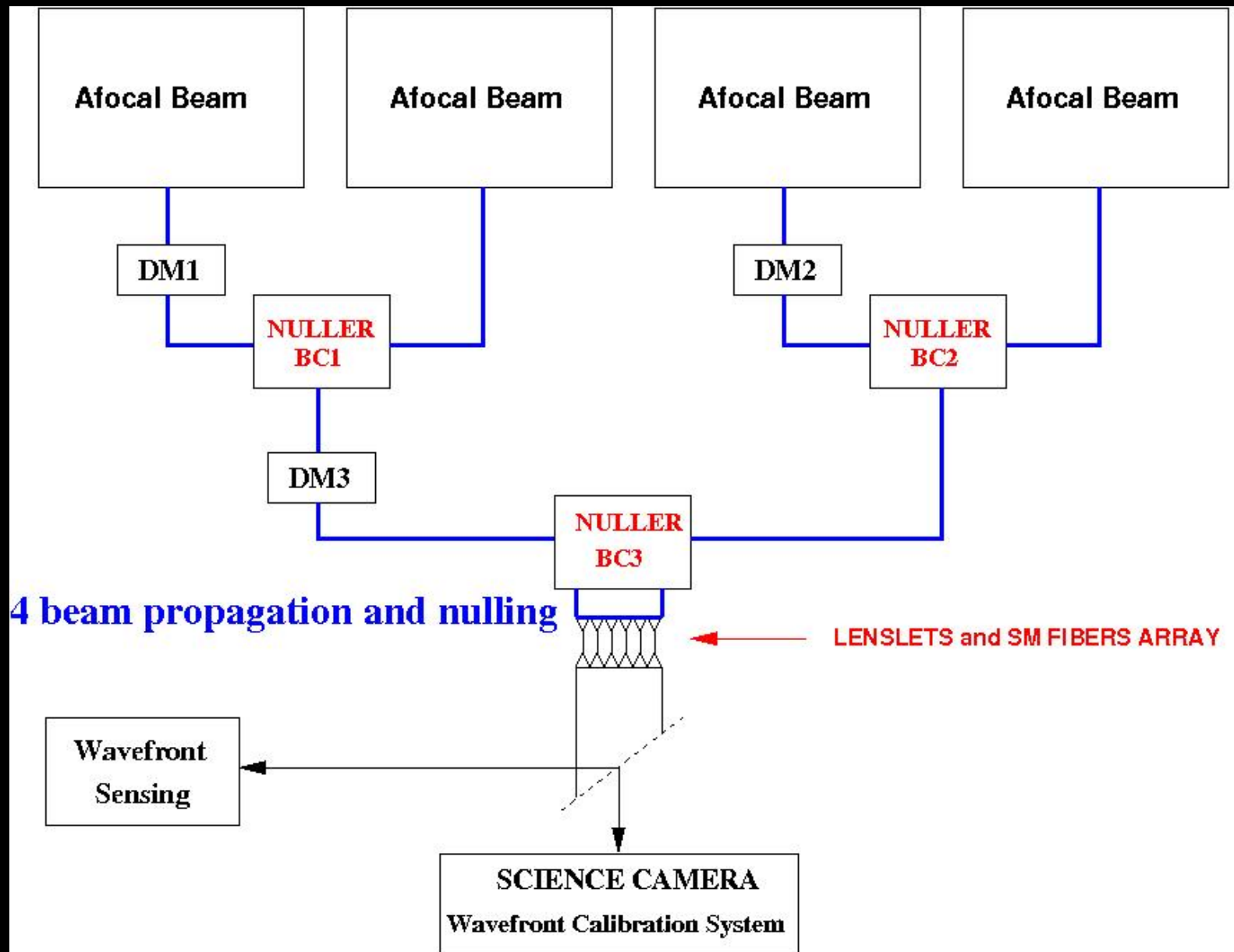
2×10^{-4}

Example: 5pm rms uncorrected surface error and 2×10^{-5} rms amplitude error (power law PSDs)

Simulations Principle and Building Blocks

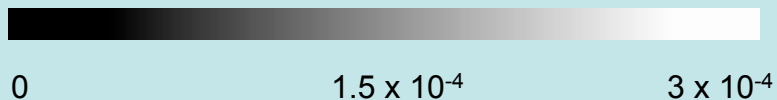
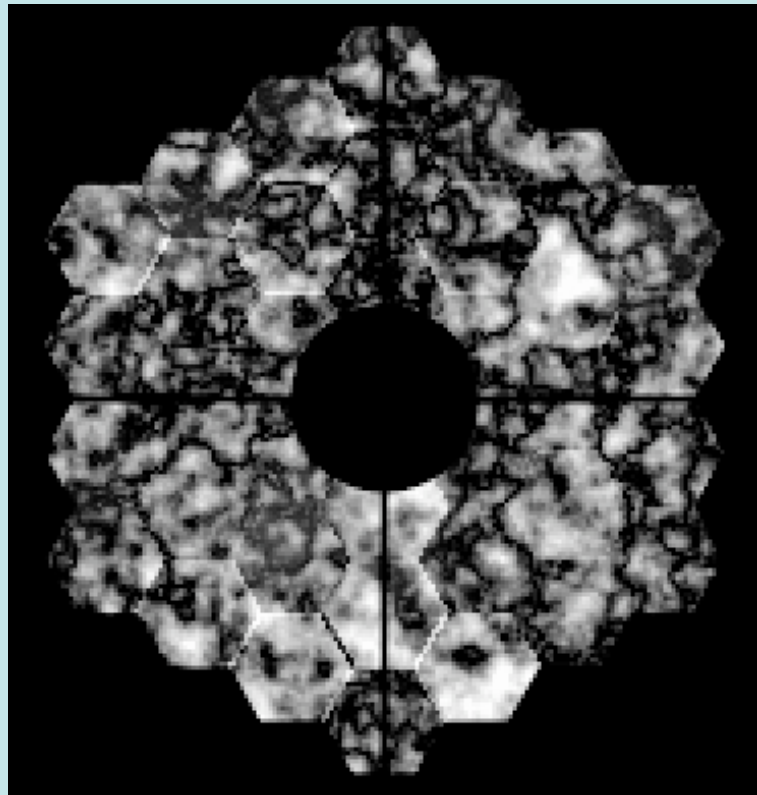
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- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level
 - ✓ Use “PROPER” Finite Diffraction Code to propagate individual beams
 - ✓ (or telescopes) distortions to Fiber Array
- ✓ Compute Nulled Field Amplitude and Phase Distribution before & after injection into each Single-Mode Fiber

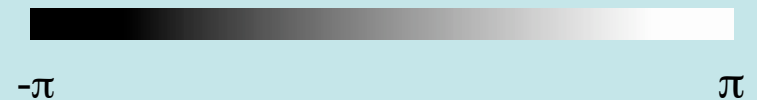
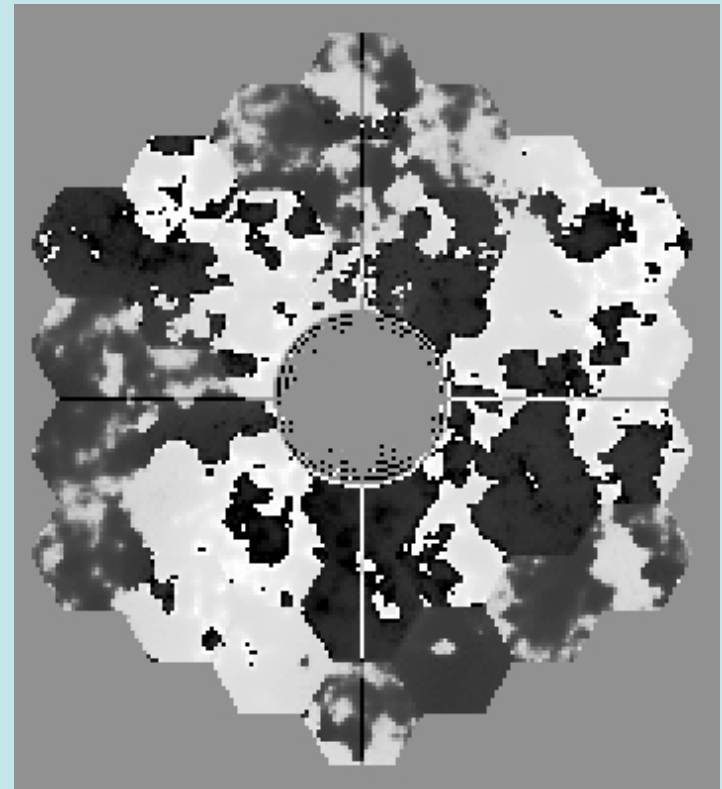


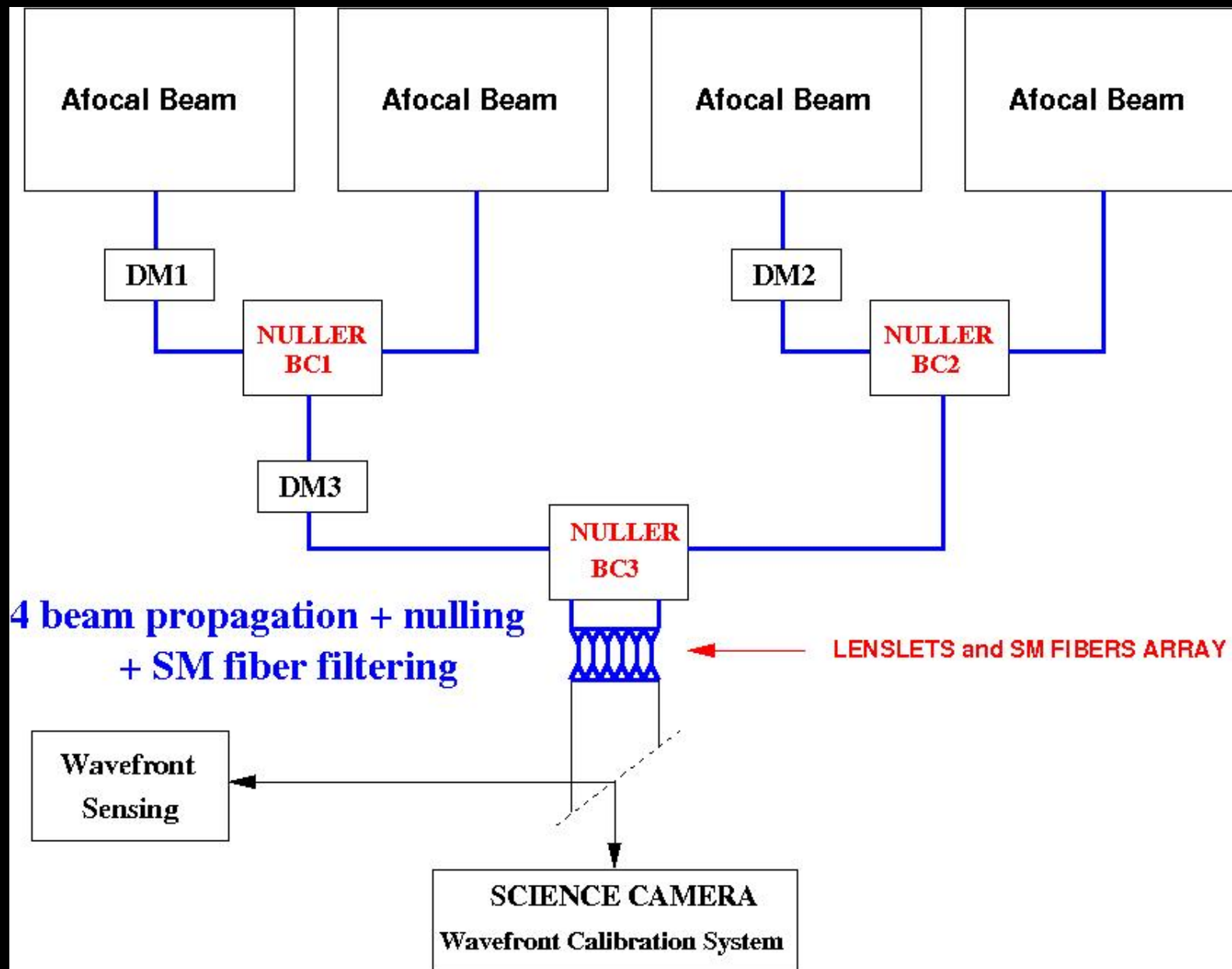
Nullled Electric Field Amplitude and Phase right after DM correction (before fibers):

Residual Amplitude



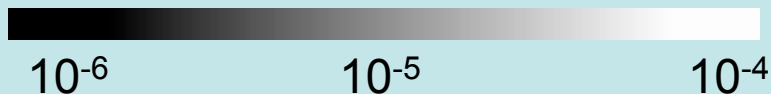
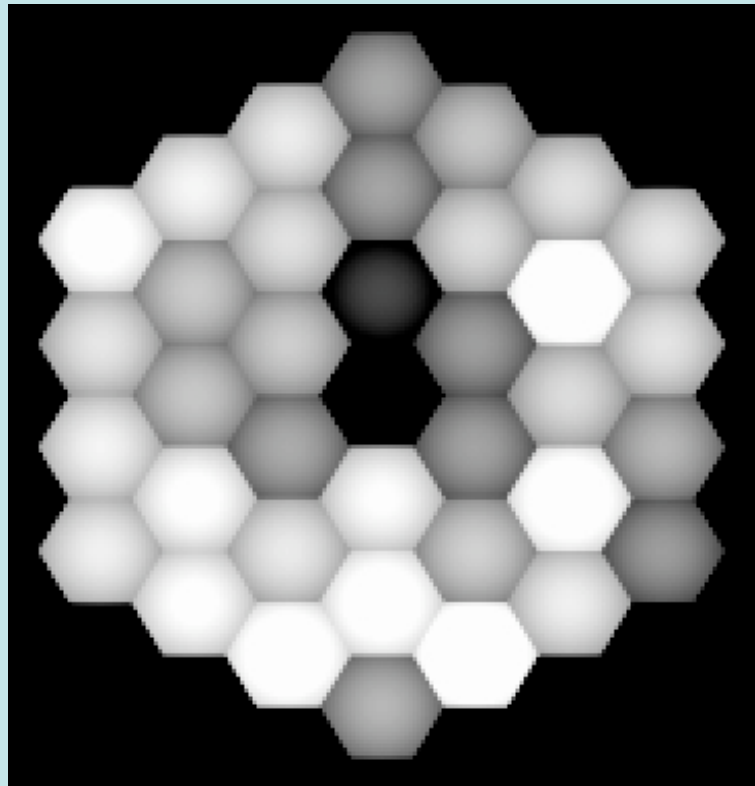
Phase (radians)





Nulling Electric Field amplitude and phase after DM correction and SM fiber filtering

Residual Amplitude



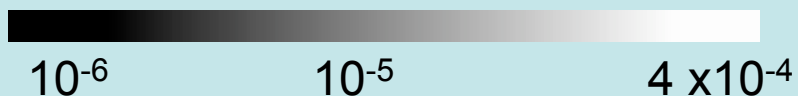
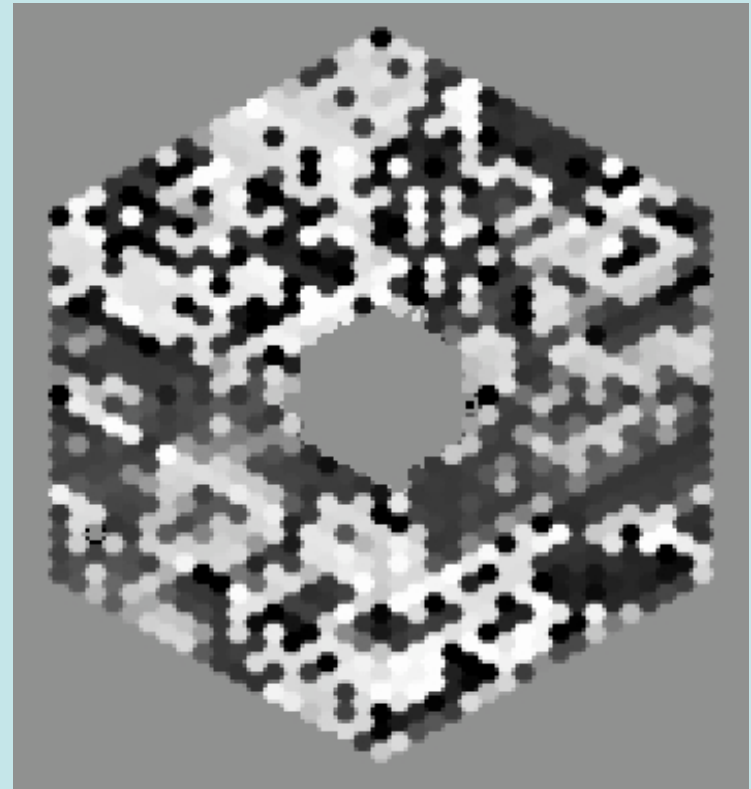
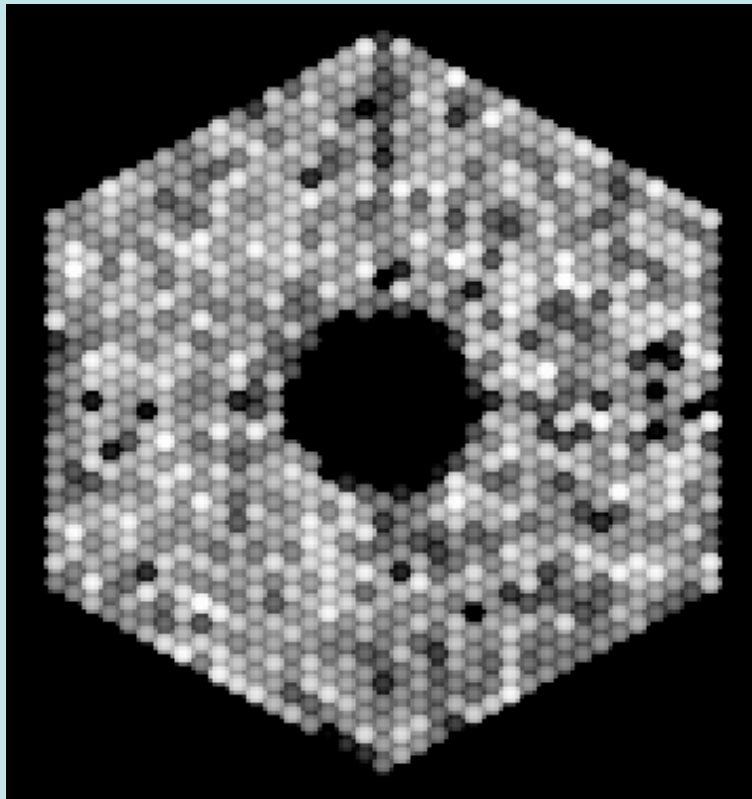
Phase (radians)



Nullled Electric Field amplitude and phase after DM correction and SM fiber filtering

Residual Amplitude

Phase (radians)



Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)
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- ✓ Use “PROPER” Finite Diffraction Code to propagate telescope distortions to Fiber Array
- ✓ Compute Nulled Field Amplitude and Phase Distribution after injection into each single-mode fiber
- ✓ Repeat for many wavelengths inside a given filter

Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

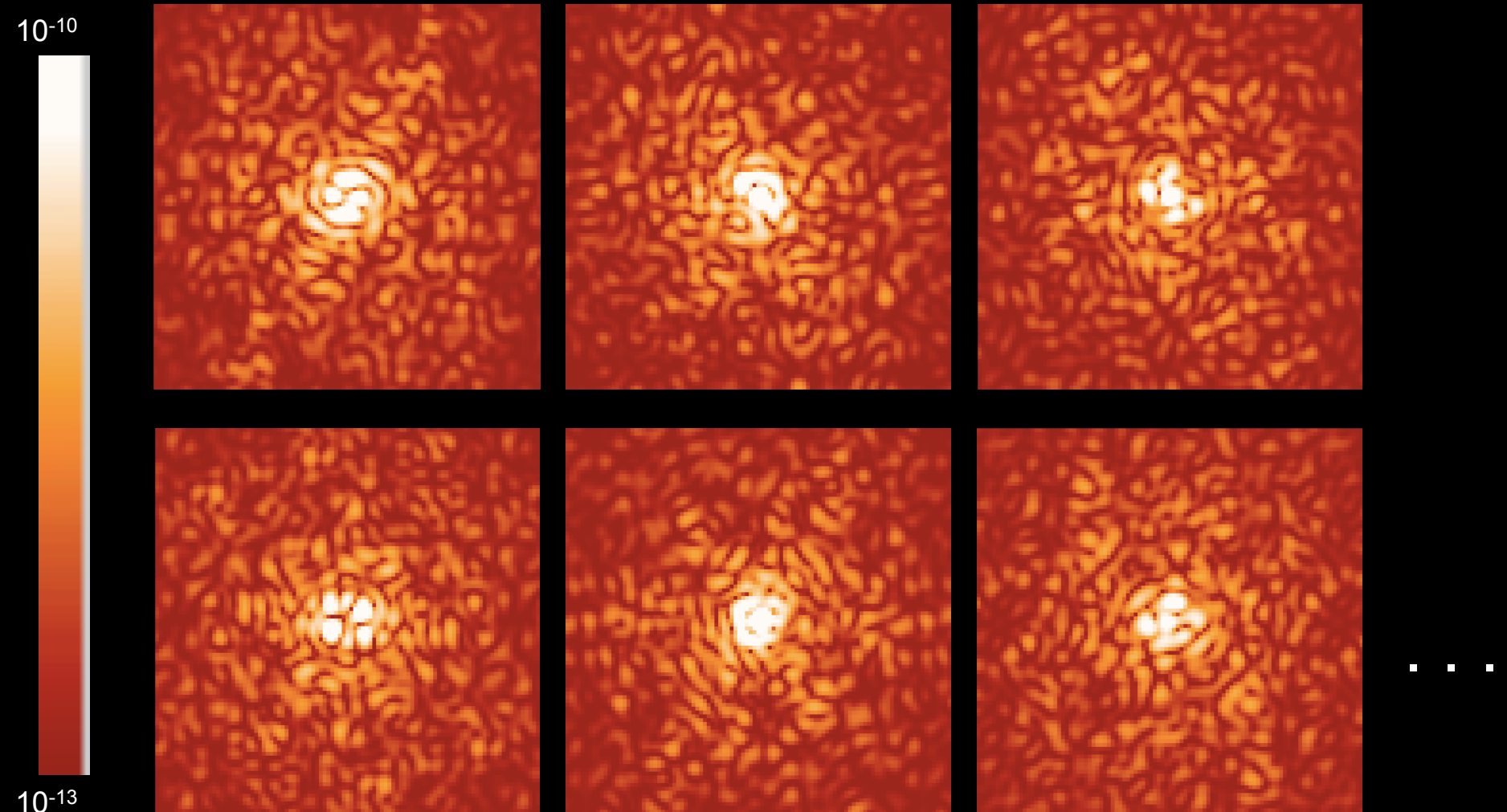
- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)
- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level
- ✓ Use “PROPER” Finite Diffraction Code to propagate telescope distortions to Fiber Array
- ✓ Compute Nulled Field Amplitude and Phase Distribution after injection into each single-mode fiber
 - ✓ Repeat for many wavelengths inside a given filter
 - ✓ Repeat and Average over many instances

Simulations Parameters

- ✓ 11 wavelengths between 500 nm and 600 nm
- ✓ Segmented DM with 1027 hexagonal actuators (independent piston and tip-tilt controls for each)
- ✓ WFC error (due to Telescope Distortions in between WFC):
 - 0.10 mas rms tip-tilt per axis
 - 10pm total phase rms with power law PSD
 - $2 \cdot 10^{-5}$ amplitude rms with power law PSD
- ✓ WF measurement error floor (induced by photon noise during WFS)
 - Residual opd= 10 pm rms per beam & per fiber.
 - Residual amplitude mismatch= $2 \cdot 10^{-5}$ per beam & per fiber
- ✓ Physical Propagation (PROPER 1024² gridsize) to Lenslet Array in Pupil Plane
- ✓ Compute injection in each of 1027 fibers
- ✓ Repeat 10 times using temporal PSD per Zernike (white PSD assumed for now)

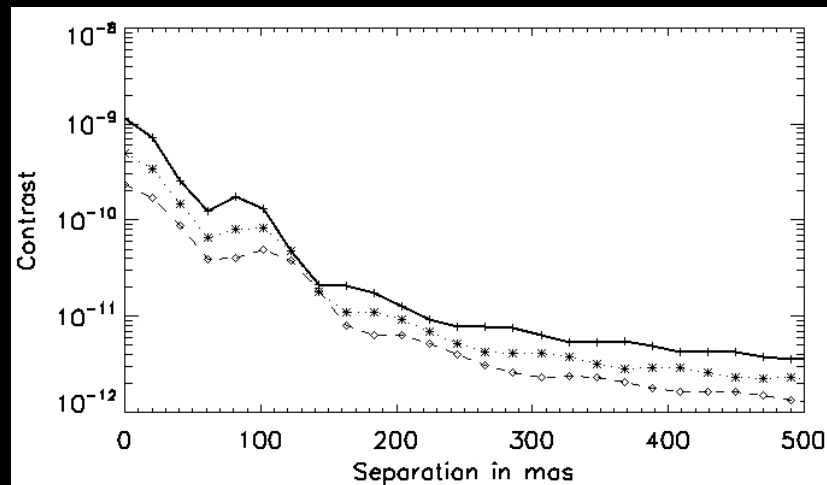
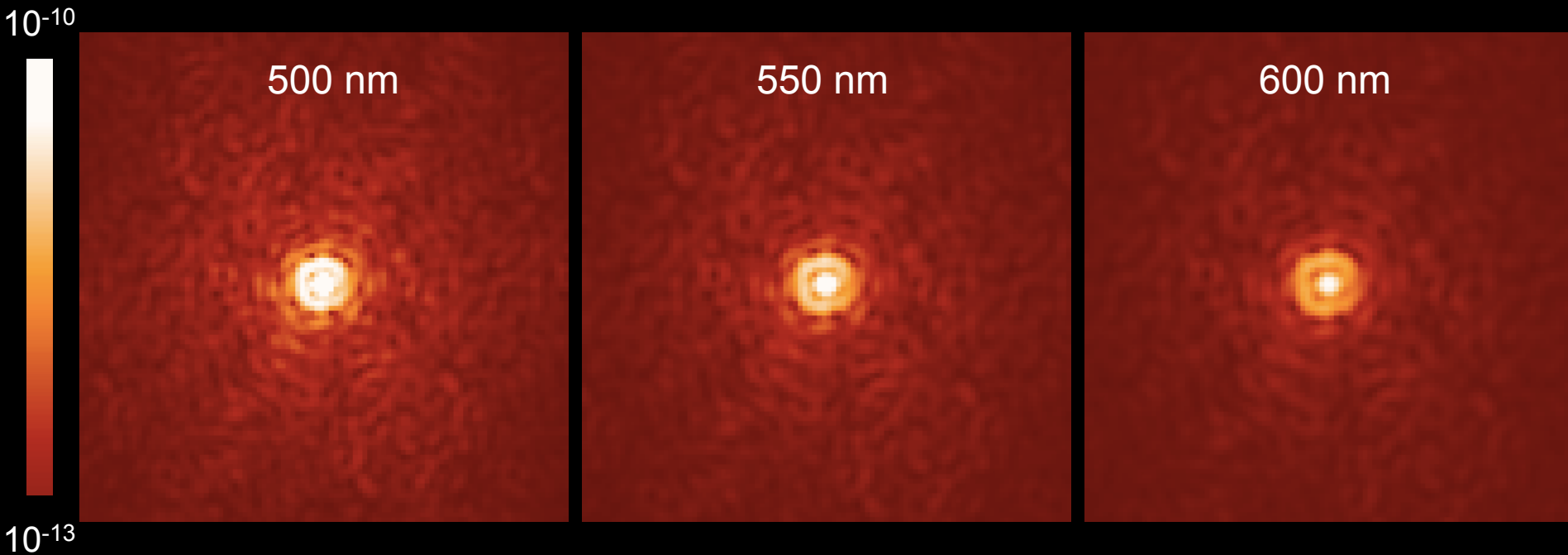
Single wavelength as a function of time

Speckle fields (central 2" x 2") at 550 nm



Contrast vs Wavelength

2"x2 " central speckle field (averaged over 10 instances):



Future Improvements to Fidelity

- ✓ Input realistic spatial/ temporal distortions at telescope level etc (from thermal/ mechanical modeling)
- ✓ Include realistic input from WFC/WFS systems
- ✓ Include Nulling BC Chromatic effects (also coupled to OPD fluctuations)
- ✓ Include all optical surfaces
- ✓ Include polarization effects
- ✓ Simulate SM fiber / lenslet array imperfections (presently assumed perfect but for $\lambda/25$ rms fiber length rms)
- ✓ Include stellar finite size

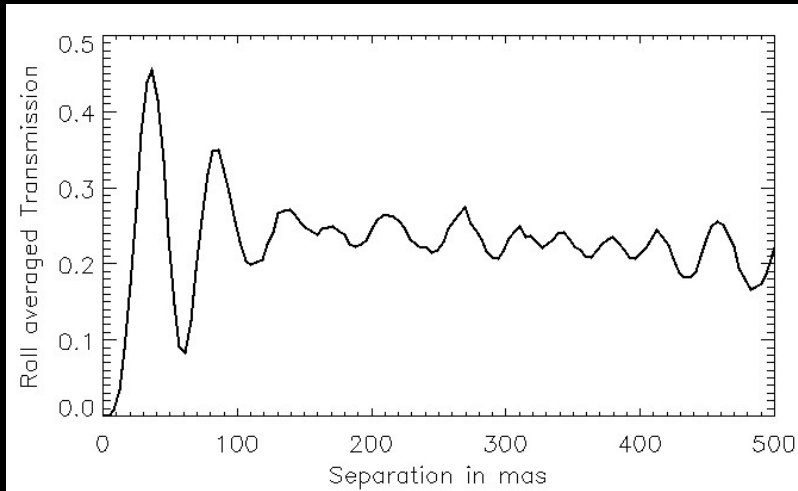
Current Status

- ✓ Main Simulation “building blocks” are in:
 - Physical Optics Propagation (PROPER) from entrance aperture to final focal plane (uses angular spectrum and/or Fresnel approximation)
 - Computes SM fibers injection (both amplitude and phase effects)
 - Folds in residual spatial and temporal wavefront distortions, specifying their PSDs (ad-hoc for now, should come from more realistic inputs in terms of perturbations, WFS and WFC performance)
- ✓ Can be used to provide top-level requirements in terms of phase and amplitude stability (WFC/WFS specs)

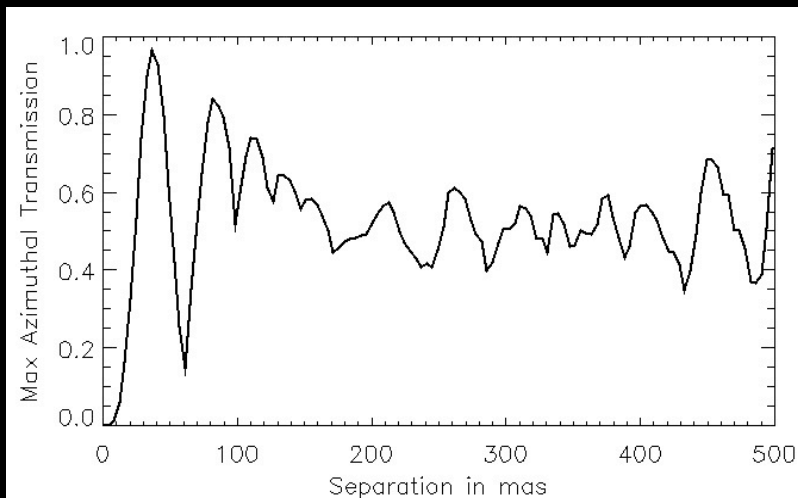
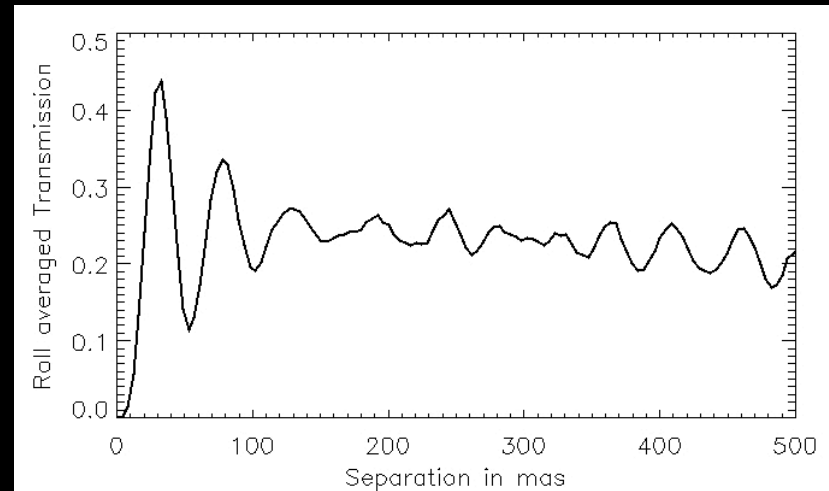
Back-up Slides

More about Sky Transmission

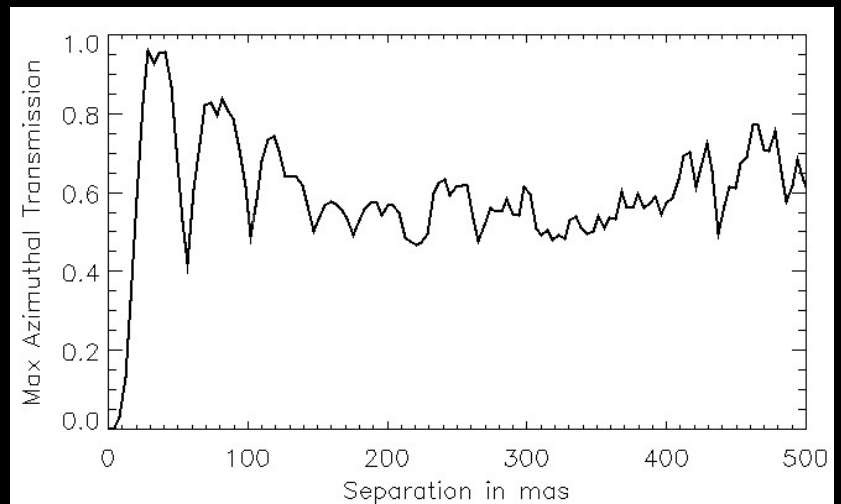
Roll average 3m x 3m



Roll average 3.75m x 2.87m

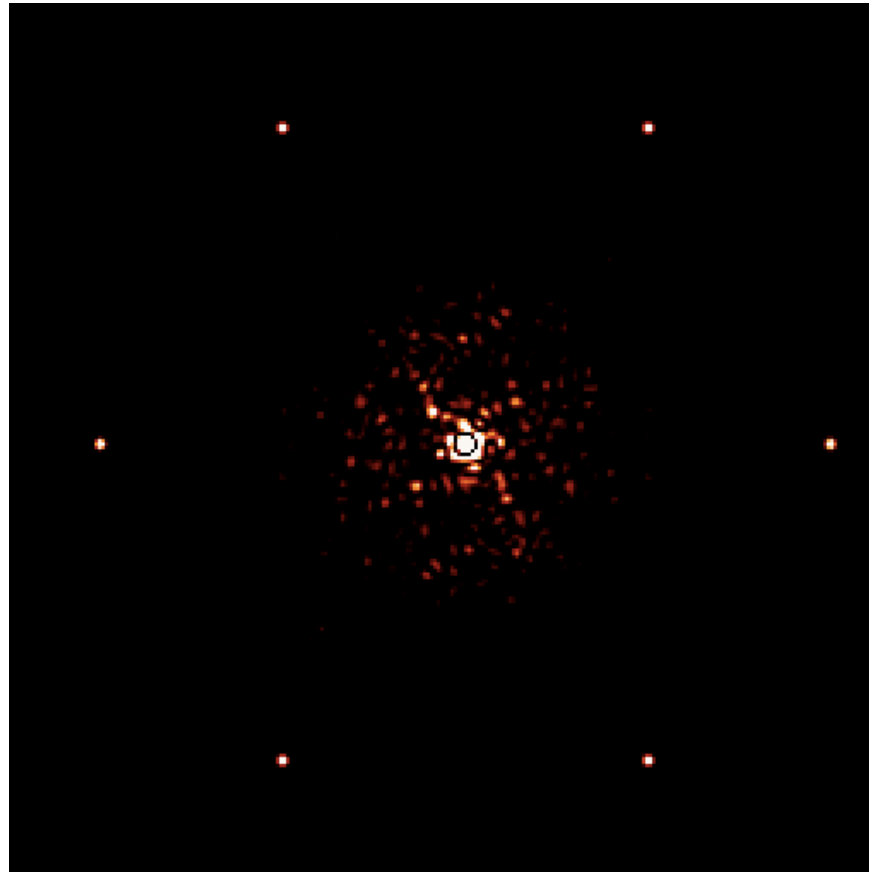


Optimum Roll 3m x 3m



Optimum Roll 3.75m x 2.87m

Replicas due to stepwise wavefront

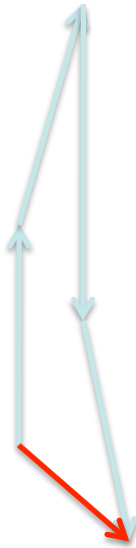


With 1027 fibers and a 2m telescope, replicas are farther than 1" in the visible

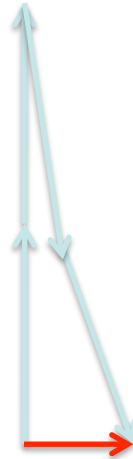
Point source speckles: centrally peaked or not?

- Answer depends on the relative phases of the partially nulled electric fields transmitted by different fibers
- In each fiber, you null 4 sub-beams coming from 4 different telescopes, with either:

Phase and amplitude errors



Mostly phase errors



Mostly amplitude errors

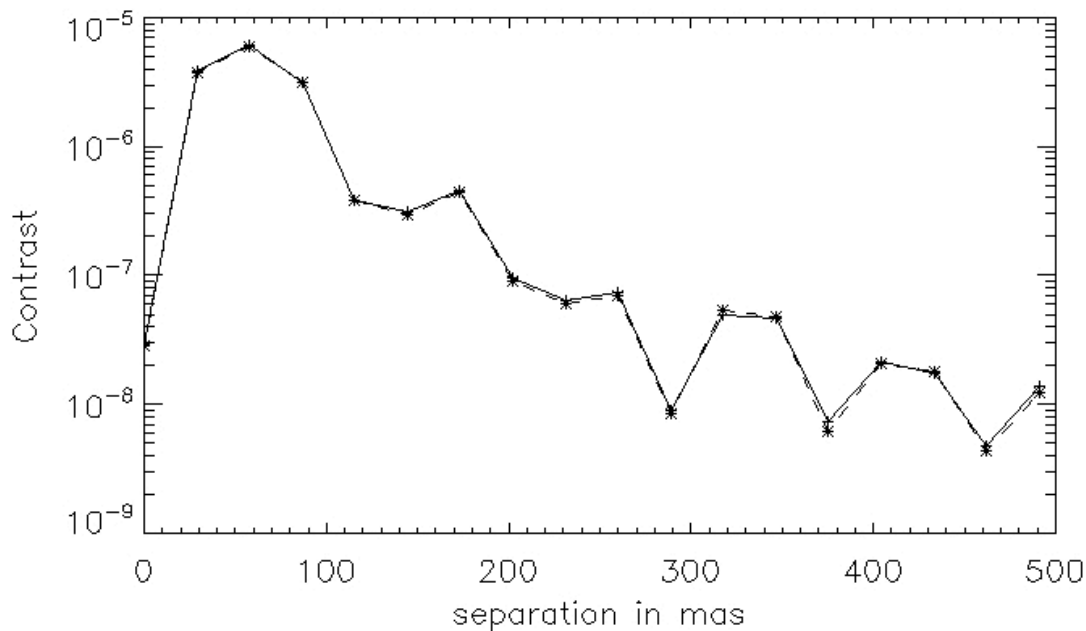


- If residual amplitude and phase defects are uncorrelated between adjacent fibers, their quasi-nulled E fields have random output phases (on-axis source residuals not centrally peaked)
 - In practice residual aberrations will dominate at low spatial frequencies (e.g. tip-tilt, defocus), and the fiber defects will be spatially correlated. Some coherence will be preserved and the residuals will be centrally peaked
- Speckles fields will anyway be centrally peaked due to stellar finite size (eq. to tip-tilt)

A few more points

- Rigid body pointing is mandatory (to get θ^4 cancellation of tip-tilt and finite stellar diameter effects)
- Contrast gain as $1/(\# \text{ fibers})$ only if random (white) spatial noise dominates. Actual behavior depends on spatio-temporal PSDs of residual phase and amplitude defects
- Does not simulate actual WFS, WFC or any image post processing based on WFS data etc

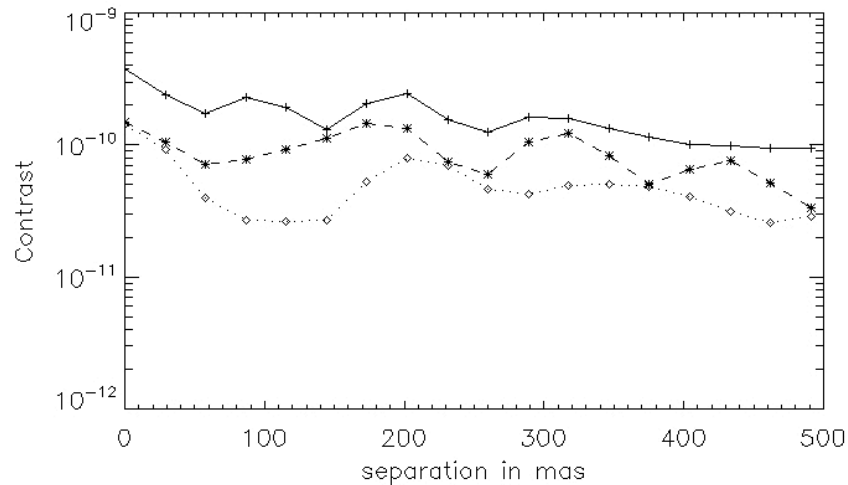
Rigid Body Behavior Mandatory for DAVINCI



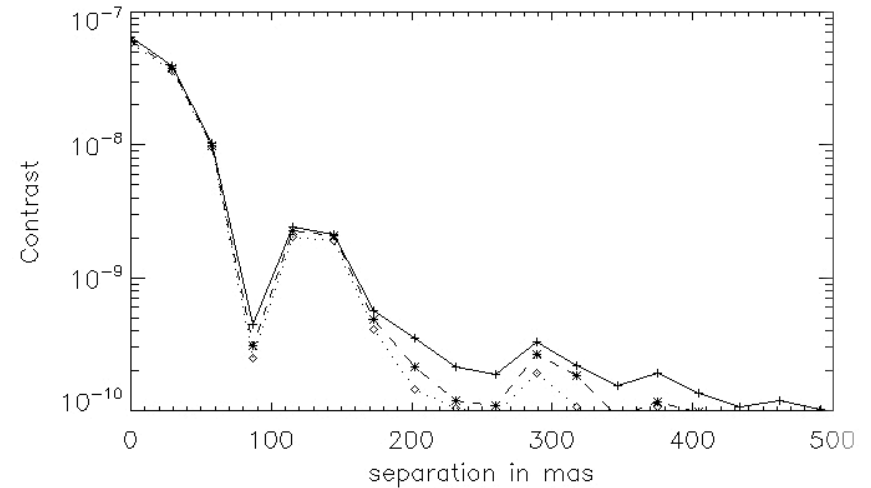
Influence of 0.5mas rms residual uncorrelated tip-tilt per telescopes
(leakage would still be prohibitive at 0.1mas rms, or for a 0.1mas star)

Impact of number of fibers on final contrast

Simulating systems with 127, 469 & 1027 fibers resp.



Assuming random distribution of fibers
residual E field phases (between 0 and 2π)
and amplitudes (10^{-4} average with 10^{-5} rms)



Same but with 0.5mas tip-tilt error